A Broad Spectral, Interdisciplinary Investigation of the Electromagnetic Properties of Sea Ice

Kenneth C. Jezek[1], Donald Perovich[2], Kenneth M. Golden[3], Charles Luther[4], David Barber[5], Prasad Gogineni[6], Thomas Grenfell[7], Arthur Jordan[8], Curt Mobley[9], Son V. Nghiem[10], Robert Onstott[11]

1. Byrd Polar Research Center, The Ohio State University, Columbus, OH
2. USA Cold Regions Research and Engineering Laboratory, Hanover, NH
3. Department of Mathematics, University of Utah, Salt Lake City, Utah
4. Office of Naval Research, Arlington, Virginia
5. Department of Geography, University of Manitoba, Canada
6. Department of Electrical Engineering, University of Kansas, Lawrence, KA
7. Department of Atmospheric Sciences, University of Washington, Seattle, WA
8. Naval Research Laboratory, Washington DC
9. Sequoia Scientific, Inc., Mercer Island, WA
10. Jet Propulsion Labotory, Pasadena, CA.
11. Environmental Research Institute of Michigan, Ann Arbor, MI.

Abstract

This paper highlights the interrelationship of research completed by a team of investigators and presented in the several individual papers comprising this Special Section on the Office of Naval Research Sponsored Sea Ice Electromagnetics Accelerated Research Initiative. The objectives of the initiative were to: understand the mechanisms and processes that link the morphological and physical properties of sea ice to its electromagnetic characteristics; develop and verify predictive models for the interaction of visible, infrared and microwave radiation with sea ice; and to develop and verify inverse scattering techniques applicable to problems involving the interaction of EM radiation with sea ice. Guiding principles for the program were that all EM data be taken with concurrent physical property data (e.g., salinity, density, roughness, etc) and that broad spectral data be acquired in as nearly a simultaneous fashion as possible. Over 30 investigators participated in laboratory, field and modeling studies that spanned the electromagnetic spectrum from radio to ultraviolet wavelengths. An interdisciplinary approach that brought together sea ice physicists, remote sensing experts (in electromagnetic measurements), and forward and inverse modelers (primarily mathematicians and EM theorists) was a hallmark of the program. Along with describing results from experiments and modeling efforts, possible paradigms for using broad spectral data in developing algorithms for analyzing remote sensing data in terms of ice concentration, age, type, and possibly thickness are briefly discussed.

1.0 Introduction

The electrical properties of sea ice growing on the open ocean are determined by its physical state, which is influenced by complex mechanical and thermodynamical forcings of the ocean and atmosphere. Winds, currents, air and water temperatures, snowfall, among other variables, contribute to the eventual roughness, texture, chemical composition and temperature gradient through the sea ice, which combine to determine its electromagnetic signature. These later properties tend to be inhomogeneous over relatively short length scales (10s of meters horizontally and 10s of cm or less vertically) and they evolve with time as the boundary conditions and the internal composition of the ice pack change. For these reasons, the analyses of electromagnetic data collected by spaceborne instruments over sea ice have tended to rely on empirical relationships between one or more electromagnetic variables (for example, brightness temperature) and a geophysical property of the ice. Numerous papers in the literature document the success of this approach for estimating sea ice concentration, type, and motion. Yet for a number of reasons, attempts to obtain a deeper understanding of the electromagnetic properties of naturally growing sea ice can be complicated [1]. For example, it is logistically difficult to measure and sample young sea ice, some processes such as the onset of flooding are transient phenomena, inhomogeneity makes sampling difficult and the opportunities to view a particular type of ice or even the same piece of ice throughout the seasonal cycle are possible only in areas of landfast sea ice. Individually, almost all of these problems can and have been overcome by investigators in the field. Collectively, however, these problems suggest the need for designing new approaches for answering fundamental questions about sea ice electromagnetic properties, namely what are the important scattering and absorption mechanisms and how are these mechanisms related to ice physical and thermodynamic properties. In turn, they pose new questions about how electrical and physical property relationships change with electromagnetic frequency, incidence angle, and polarization.

In 1992, the Office of Naval Research began a new Accelerated Research Initiative titled "Electromagnetic Properties of Sea Ice". More than thirty investigators from 20 institutions in the U.S. and Canada participated in the project. The conceptual goal of the initiative is shown schematically in figure 1 and on the cover of this issue. Essentially, the program sought to relate the measured electromagnetic signature of sea ice to the physical properties of the ice through forward models. In turn, the forward models were used to develop inverse methods through which ice geophysical properties (thickness, roughness, etc.) could be determined from remotely sensed electromagnetic data. The ARI had several important attributes that extended it beyond previous studies. First, the range of observations spanned the electromagnetic spectrum from the radio band to ultraviolet. Second, simultaneous, broad-spectral observations of the same ice samples occurred concurrently with observations of snow and ice physical properties. Third, there was a deliberate effort to more directly involve members of the electromagnetic modeling community in the end-to-end experiment design and to purposely include inverse modelers. Fourth, the ARI involved laboratory, field and theoretical components in a unifying process which included careful laboratory observations, field measurements to verify results, and the development of theory and predictive models. Laboratory work extended experiments begun in the 1980's at the USA Cold Regions Research and Engineering Laboratory. Fieldwork validated observations made in the laboratory and

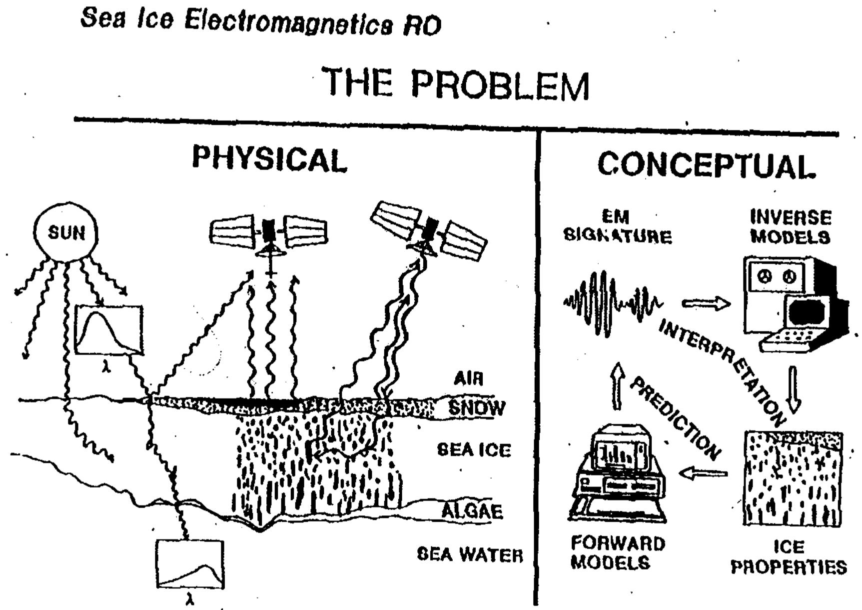

Figure 1. Conceptual diagram of the ONR Sea Ice Electromagnetics Accelerated Research Iniative. The diagram captures key objectives including the broad spectral attribute of the ARI and the connections between physical observations, forward modeling and inverse modelling.

increased the range of ice types studied as part of the ARI. Theoretical work aimed at building a model framework for interpreting results and also for furthering the basic mathematics of inverse modeling as applied to geophysical problems.

The interdisciplinary nature of the ARI represented both the greatest strength and most significant challenge of the overall effort. Team members included passive and active microwave remote sensing experts, optical oceanographers, sea ice physicists, and mathematicians, each of whom contributed essential knowledge about the sea ice electromagnetics problem. The challenge was to assemble each piece of knowledge gleaned from across the electromagnetic spectrum of interest into a broad spectral model useful for recovering sea ice geophysical properties (snow and ice thickness, thermodynamic state, etc) from remote sensing data.

2.0 Background

The first series of USA Cold Regions Research and Engineering Laboratory Experiments (CRRELEX), begun in 1984, were designed to confront some of the difficulties encountered in fieldwork. The CRRELEX approach was to grow sea ice in a carefully constrained, laboratory environment where ice physical properties could be manipulated and documented. Microwave experiments were conducted under an umbrella set of conditions that included: 1) growth and maintenance of uniform ice sheets of limited and well documented physical properties; 2) use of multiple sensors to collect data simultaneously from the same ice sheet; 3) coordinated interpretation of all the electromagnetic observations of the ice with the simultaneously measured ice physical properties. As the experiments progressed, two more facets were added to the measurement objectives. First, data collection was to be rigorously coupled with particular models and modeling efforts. Second, time series data were to be collected. This last point arose because observations showed that measurable changes in electrical properties occur at every stage of ice development (figure 2.)

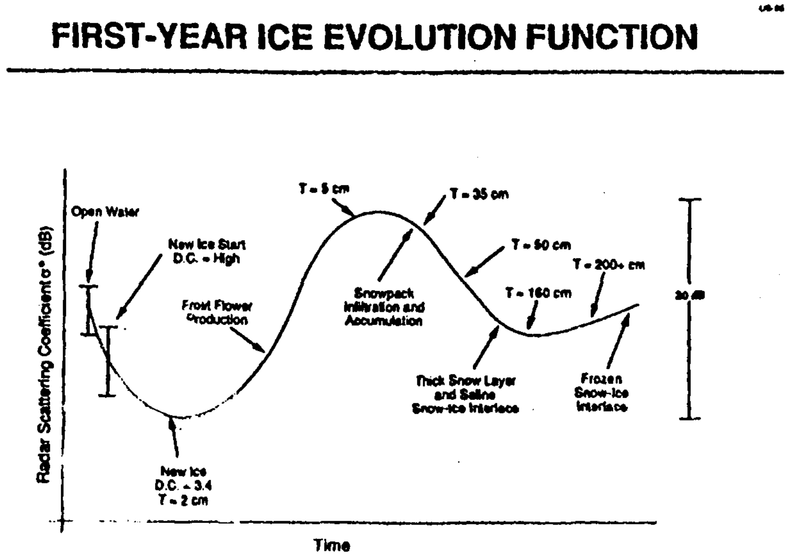

Figure 2. Illustration of the time varying backscatter signature of sea ice throughout its development. A key objective of the ARI was to quantify this relationship across the electromagnetic spectrum.

Experiments completed during the first CRRELEX program demonstrated a capability to grow saline ice with a predefined range of physical properties. These include thin ice with varying crystalline textures and salinity gradients, roughened ice that included a range of roughness elements, desalinated ice and snow-covered ice of various thickness. These data were used to compute the permittivity of thin ice, to demonstrate the complex relationship between permittivity and brine migration that occurs as ice grows, the influence of tharmal variations, and the effect of snow on ice physical and electrical properties. Theoretical work, which concentrated on the microwave part of the spectrum, established frequency bounds on when and under what conditions volume scatter or surface scatter from sea ice dominated the microwave signature.

3.0 ARI Science Goals

The ARI built upon previous research by greatly increasing spectral coverage, investigating more ice types and ice growth scenarios, and establishing an inverse modeling component. Research was organized to reach four overarching goals:

1) understand the mechanisms and processes that link the morphological/physical and the electromagnetic properties of sea ice,
2) further develop and verify predictive models for the interaction of visible, infrared and microwave radiation with sea ice,
3) develop and verify selected techniques in the mathematical theory of inverse scattering that are applicable to problems arising in the interaction of EM radiation with sea ice,
4) use broad spectral data to develop robust spectral models of sea ice electromagnetic signatures.

More specific objectives included:

1) identify and isolate basic scattering sources and mechanisms (surface, volume) and determine their individual effects on reflection, transmission, and attenuation,
2) quantify sea ice electromagnetic properties to unambiguously identify ice types and to determine deformation characteristics,
3) measure the influence of snow cover over sea ice on energy reflection, transmission and absorption,
4) develop physical models of EM forward and inverse scattering from sea ice, that are computationally practicable and applicable to interpretation of remote sensing data.

4.0 Approach

The ARI began in 1992 with laboratory experiments in a vastly upgraded research facility at the USA Cold Regions Research and Engineering Laboratory located in Hanover, New Hampshire. Laboratory research, field studies and theoretical work continued through 1995. During the last two years of ARI sponsored research, efforts focused on integrating electromagnetic and physical properties data sets for concurrent use in model development and verification.

Laboratory experiments were conducted in 1993, 1994 and 1995 in the specially designed Geophysical Research Facility at CRREL. The Geophysical Research Facility was used by all investigators and provided a common focus for research (figure 3). Experiments that required exceptional environmental control were conducted in an indoor laboratory which could be used for careful studies of the effects of changing temperature, humidity and surface roughness.

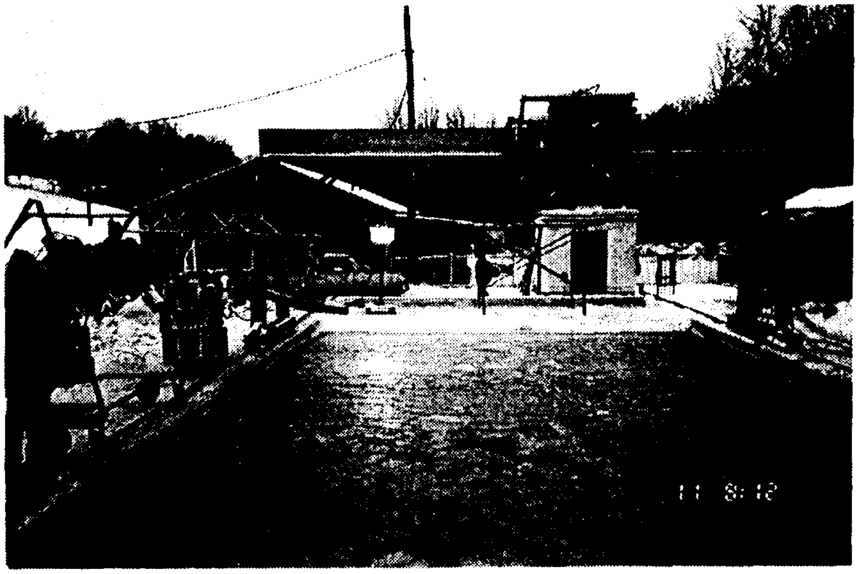

Figure 3. The sea ice test facility constructed at the USA Cold Regions Research and Engineering Laboratory. Pictured is pancake ice; a type of ice that forms in the presence of a wave field.Observations were made from the sides of the pond and from a movable gantry. A removable, refrigerated roof was used to regulate surface conditions including temperature and the amount of snow fall..

A wide range of ice types in various morphological states, snow cover, water and meteorological conditions were successfully simulated in the laboratory environment. Most thin ice types including pancake ice were studied during the course of these laboratory experiments. As well, studies of the EM/physical property changes during ice growth from open water through thicknesses representing thick first year ice were accomplished.

The major field component of the EM-ARI was an experiment at Barrow, Alaska, from 20 April to 10 May 1994. The focus of the experiment was to obtain a complete description of the physical and electromagnetic properties for thin, first year, and multiyear ice and snow for verification of laboratory results. Two first-year sites were studied in detail during the experiment: 1.25 m thick ice in the Chukchi Sea (Site 1) and 1.7 m thick ice in the Beaufort Sea (Site 2). In both cases the ice was snow covered and undeformed. In addition to the contrast in thickness, Site 1 had higher level of biota in the ice and greater concentrations of particulates in the snow than Site 2. Optical measurements were made of total albedo, spectral albedo, and transmittance (300-1000 nm), the radiance distribution within the ice and beam spread functions (BSFs) along both vertical and horizontal paths within the ice. Passive and active microwave observations of emissivity and radar backscatter were also made. After observations of the snow-covered ice were completed, the snow was removed and measurements of bare first-year ice were made. Snow and ice cores were collected for later analysis in the laboratory.

Two smaller field experiments occurred in 1995 at Barrow, Alaska and at Resolute Bay, Northwest Territories. The later was done in close cooperation with the Seasonal Sea Ice Monitoring and Modeling Site (SIMMS) program.

5.0 Results

Principal results of laboratory experiments, field experiments, and theoretical studies conducted throughout the 5 year ARI period from 1992 to 1997 are summarized herein.

5.1 Laboratory Component

Laboratory experiments conducted as part of the sea ice electromagnetics initiative had three major objectives. These were

1) conduct measurements in a controlled environment,
2) conduct measurements that would be difficult to execute in the field,
3) bridge lab and field measurements through field verification of lab results and extend lab simulations to a broader range of field environments.

Details of the laboratory experiments are described in the accompanying papers [2,3,4]. Highlights include:

- measurements and estimates of dielectric permittivity and index of refraction of sea ice and its components,
- contributions of microwave volume and surface scattering separated for different incidence angles (0° to 60°), frequencies (P- to Ka-band) and polarizations,
- empirical relationships between ice thickness and microwave scatter/emission for thin ice types,
- transition in microwave polarization ratios from new ice to first year ice associated with the formation of a low density surface layer (snow or frost flowers),
- broad spectral measurements of frost flower and pancake ice signature-evolution,
- strong effect on microwave properties of snow covered ice and modification of ice surface roughness by brine wicking and brine expulsion;
- enhancement of C-band backscatter at normal incidence after surface flooding; decrease in backscatter at oblique incidence; co-polarization ratios increased after flooding;
- preferential damping, by sea ice, of UV radiation relative to photosynthetically active radiation;
- correlated changes in optical transmission and microwave backscatter with time varying evolution of internal ice structure;
- enhanced sensitivity at optical frequencies to changes in ice freeboard (number density of gas filled inclusions) relative to microwave backscatter;
- Optical frequency sensitivity to changing brine pocket size through increasing transmission loss and albedo with temperature changes. Microwave backscatter increased with temperature because of increased dielectric constant

Figure 4 illustrates one of the unique results from the laboratory phase. Thermal infrared measurements were collected during the formation and decay of thin layers of ice on the surface of saline water filling the Geophysical Research Facility tank. Because of the calm, stratified condition of the tank, a thin freshwater layer formed from melting of snow and ice. This combination caused the pond to appear warmer than seawater at its melting point and warmer than surrounding materials with temperatures closer to ambient air temperatures. This complicated infrared signature has implications when using remote sensing data for estimating the surface heat budget and heat flux.

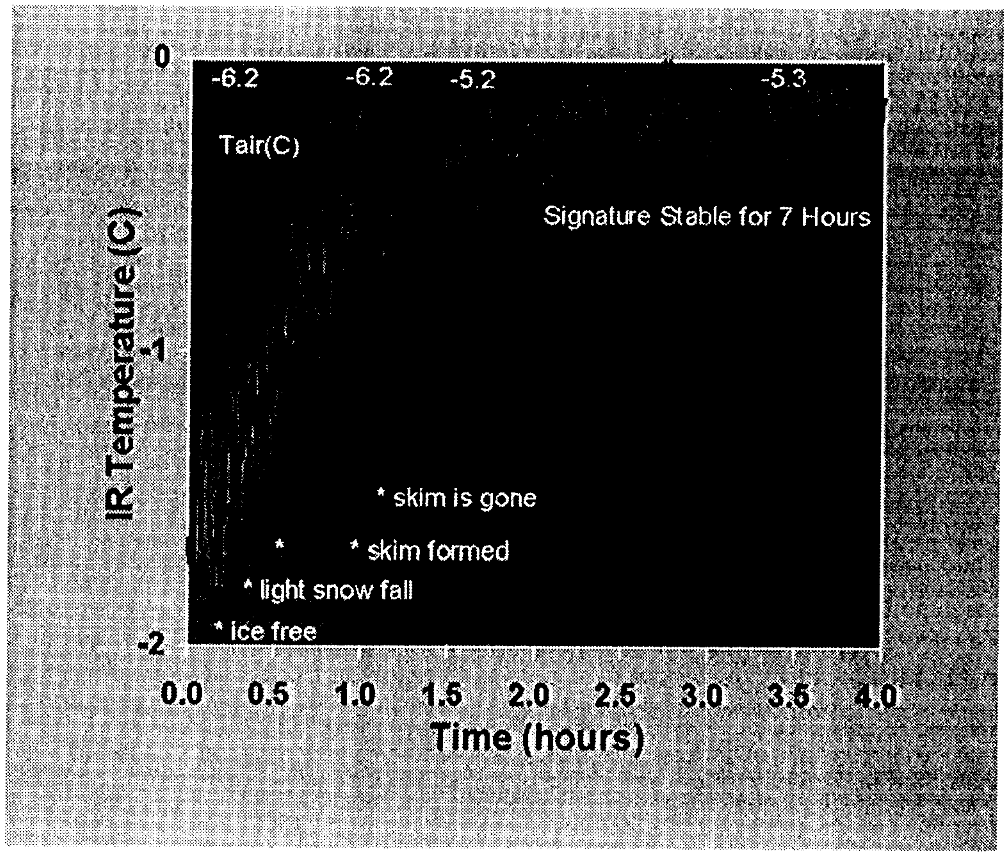

Figure 4. Plot of pond surface temperatures estimated from thermal infrared brightness temperatures are plotted with time. Surface changes (ice free, snow fall, ice skim, skim melted) are indicated along with measured air temperatures which remained below -5 degrees C for the entire measurement period.

Laboratory work also resulted in several technical advances. These included: the first application of plane wave illumination structures for studying microwave backscatter from a distributed target [5]; development of ultra-wideband microwave radars; developing techniques for measuring dielectric constants on ice samples and in situ; innovative techniques for creating carefully controlled rough surfaces; construction and application of polarimetric and UHF radiometers. An example of the ultrawide band radar results is shown in figure 5 which illustrates the response of a plane wave normally incident on saline ice covered by a 5-cm thick snow layer. The time-domain response is constructed from step frequency data collected between 2 and 18 GHz. Returns from the snow and ice surfaces are easily resolvable enabling a separation of scattering contributions from the different constituents. This example demonstrates the dominance of scattering from the snow-ice interface over the air-snow interface for this situation.

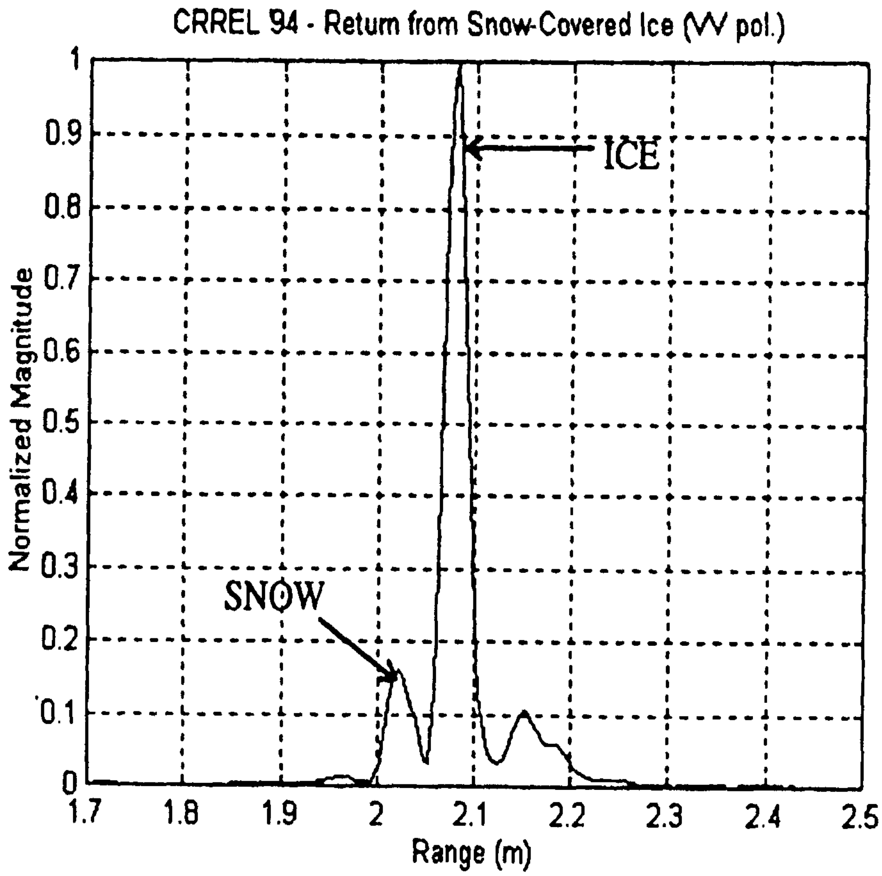

Figure 5. Wideband, plane-wave normally incident on saline ice covered by a 5 cm thick snow layer.

5.2 Field Component

Field Observations were an integral part of the sea ice ARI. The field studies had three broad objectives:

1) Determine if conclusions from the laboratory experiments were confirmed in the field;
2) Extend the laboratory work to include additional ice types and conditions;
3) Add new experimental techniques and investigate phenomena that could not be studied in the laboratory.

Results of the field studies are summarized in [6], with details available in individual reports [7,8,9,10]. Significant results from the field program include

- in situ measurements of light scattering parallel and perpendicular to oriented ice crystals,
- the size distribution of air bubbles can be described by a two-parameter log normal distribution,
- the presence of particulates in the surface layer of sea ice reduces albedo and increases absorption,
- the in-ice radiance distribution is strongly influenced by particulates and dissolved materials in the ice,
- the Stokes vector of reflected light increases in the plane of incidence of the solar beam, most notably for smooth surfaces, such as melt ponds and bare ice,
- as the snow cover melts away the average albedo decreases and the horizontal variability in albedo increases,
- visible wavelength albedo for melt pond albedos are influenced by pond depth, the structure of the underlying ice and the presence of particulates,
- anisotropic microwave permittivity caused by brine pocket asymetry in columnar ice.

The field program complemented the laboratory experiments and enabled the entire cycle of first year ice from initial growth to the onset of melt to be examined. Measurements of initial ice growth were made in the laboratory, where controlled conditions and easy access to the thin ice were major advantages. The temporal evolution of sea ice physical and electromagnetic properties during the spring-summer transition for thick first-year ice (1.6 m) were investigated in the field. Figure 6 illustrates the synergy between the laboratory and field studies. Albedos at 500 nm, 1000 nm and integrated over the solar spectrum (300-3000 nm) are plotted for initial ice growth and for the transition from snow-covered ice to melt ponds. Scattering coefficients for snow and ice are roughly comparable at 500 and 1000 nm, but the absorption coefficient at 1000 nm is more than two orders of magnitude greater. Because of this, the relative contribution of volume scattering is much greater at 500 nm. Albedos at 1000 nm are determined primarily by conditions in the top few centimeters of the medium, while deeper levels make a contribution at 500 nm.

New optical techniques were developed for measuring beam spread functions over a full 360 degrees in angle, and as a function of depth, along horizontal paths in the ice. Such measurements provide a new tool for understanding the relationships between ice physical and optical properties. In particular, horizontal BSF measurements, which are made between coring holes drilled in the ice, can provide important constraints on inverse algorithms for retrieving ice properties, such as scattering phase functions, that are difficult to measure directly.

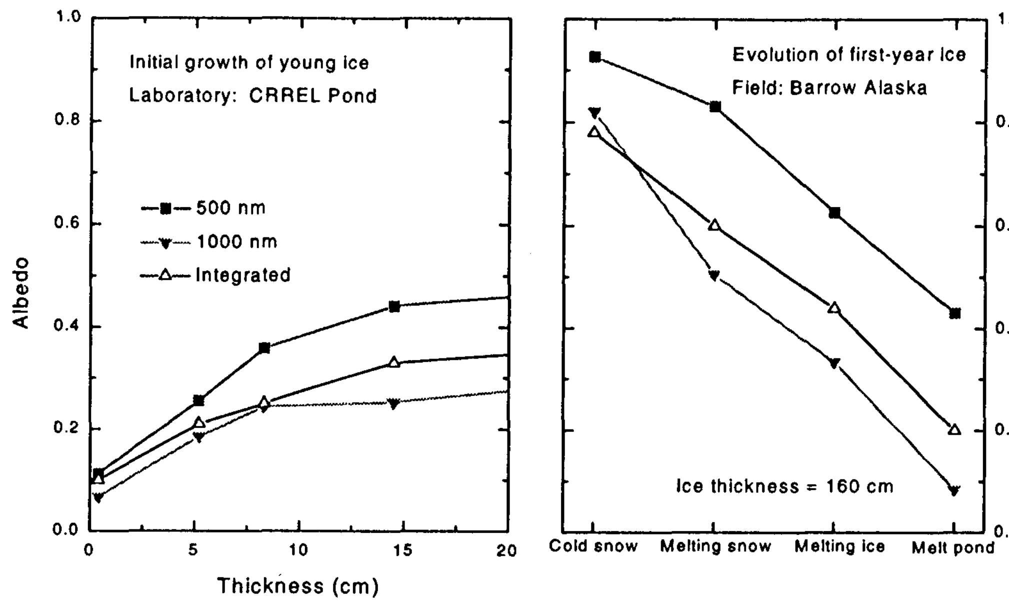

Figure 6. A compilation of laboratory and field observations showing the evolution of albedo during the initial growth of young ice and during the seasonal transition from spring to summer. Results are presented for 500 nm, 1000 nm and spectral albedos at 500 nm and 1000 nm are plotted, as well as values integrated over the solar spectrum from 300 nm to 3000 nm.

The combination of field and laboratory studies contributed to knowledge about microwave backscatter from snow covered ice. The thermodynamic behavior of the snow ice interface, along with snow thickness and grain properties, turns out to be an important control on overall scattering strength.. Earlier laboratory work [11,12] at 13.9 Ghz showed that interface wetness either due to brine wicking or flooding increased backscatter by many dB. The combination of interface roughness and increased dielectric constant explained the observation. Field work [13] demonstrated that there was much less of an effect at C-band because the longer wavelength signal responded less to the interface roughness. In fact backscatter from dry snow covered ice was a slightly stronger scatter than flooded ice. An even larger damping of backscatter (4-8 dB decrease) was observed during the ARI [14] when a new ice surface was flooded with saline water. Wide band radar data acquired during the ARI support these observation and suggest the crossover in dominant scattering mechanisms occurs between 9 and 10 GHz for new snow on new ice [3,4]. Above the cross over frequency, the signal responds to the presence of snow because scattering is increased by both snow thickness and interface wetness. Observations suggest that interface wetness causes the most important modulation on scattering from thin snow cover. As the ice and snow thicken and age, a contrast reversal occurs at C-band. Observations at Barrow revealed that scattering from snow covered first year ice was 5 dB higher than bare ice. These results suggest that radars operating above 9 GHz are better suited to studies of both the interface and volumetric properties of snow covered ice.

Within the ARI a second field experiment was conducted as part of the Canadian lead Seasonal Sea Ice Monitoring and Modelling Experiment [15]. The objective of this field experiment was to examine ice types typical of the Canadian high arctic and to tie the geophysical and scattering characteristics of the CRRELex work to the interannual database available from the SIMMS experiment.. By combining geophysical observations with in situ scatterometer and spaceborne ERS data the authors were able to show that the scattering over thick first-year sea ice was affected by the thermodynamic characteristics of the snow/ice system [16]. Further examination of the phenomena confirmed that the thermodynamics of the snow cover affect wave propagation, attenuation, and scattering through the control that brine volume exerts on interfacial characteristics of the snow and ice layers. The effect is subtle and specific to certain ranges of salinity, surface roughness, and thickness of sea ice. The authors concluded that within the conditions of this case study there is a detectable change in scattering over low magnitude targets. These scattering surfaces correspond to thick smooth first-year sea ice. Changes are not detectable over multiyear, thin smooth first-year (<40cm), or rough forms of first-year sea ice. The change in scattering between air temperatures of -18 and -11°C (i.e., there was no water in liquid phase in the snow) resulted in a increase in the snow/ice interface temperature. This change caused an increase in the complex permittivity of the snow basal layer and within the surface frazil layer of the sea ice. The change in scattering is well within the detection capabilities of most spaceborne SAR (1-3 dB). Through diagnostic application of a forward scattering model [17] the authors attributed the physical mechanisms, in order of relevance to: the basal layer snow grains; the brine pockets within this basal layer; the brine pockets within the frazil layer and the ice surface roughness.

An increase in air temperature was shown to increase scattering over smooth first-year sea ice. The increase in scattering appears to be related, at least in the first order, to the thickness of the snow cover over first-year sea ice. For a given ice thickness and air temperature change, a thick snow cover will result in a smaller change in the snow/ice interface temperature (due to the thermal conductivity of the snow cover). This small change in the interface temperature will result in a relatively small change in the brine volume at the interface and the resulting complex permittivity, thereby producing a relatively small change in scattering. A thin snow cover produces a larger interface temperature change and thereby a larger change in scattering. It is important to note that the microwave scattering change is responding to the brine volume and complex permittivity of the snow/ice interface and that this interface will be dominated by atmospheric forcing whenever the ice is sufficiently thick to reduce the oceanic heat flux. The authors used to phenomena to recreate an ordination of the snow thickness distributions over thick smooth first-year sea ice within a 100 km radius of the field site [18].

5.3 Theory Component

The goal of theoretical research conducted under the ARI was to develop techniques for using data on the electromagnetic fields scattered or emitted by sea ice during remote sensing to deduce the physical properties of the sea ice pack (figure 7). Parameters included in the forward models, some of which were deduced from the inverse models are illusrated in the figure. Models were developed to address physical properties from the microwave to the optical parts of the spectrum. Mobley and others [19] discuss progress on interpretation of observations across the optical portion of the spectrum. Golden and others [20,21] discuss general forward and inverse models which are applicable to the interaction of electromagnetic waves with complex random media, but which are particularly suited to the microwave region for applications to sea ice.

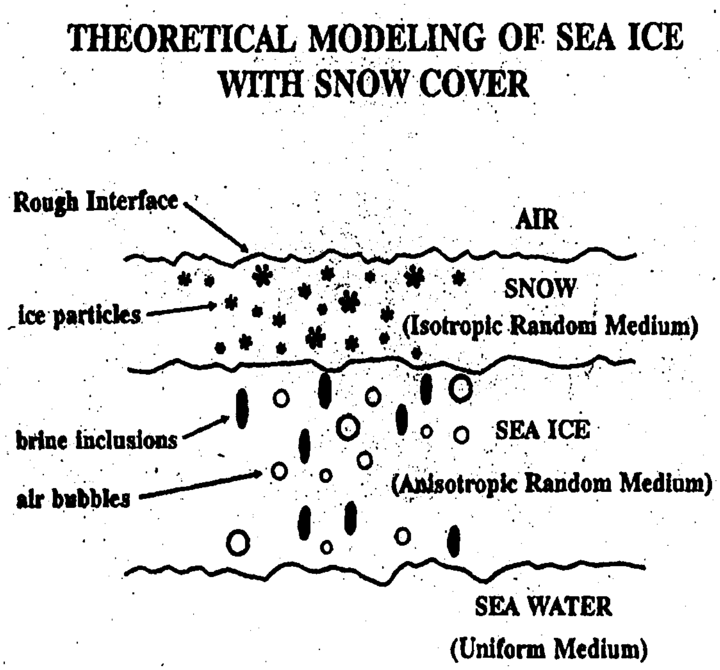

Figure 7. Illustration of the structural components of sea ice incorporated into modeling studies.

Analyses of optical data show that classical radiative transfer theory is adequate for predicting visible wavelength albedoes, transmittances, and BSFs. It was also shown that is possible to begin with ice physical properties such as brine pocket and bubble size distributions and to predict ice scattering and absorbing properties. When used in radiative transfer models, the results lead to predicted albedos, transmittances, and BSF's that are in good agreement with observations. Beam spread functions measured along horizontal paths within the ice provided an important test of the scattering properties of sea ice as predicted from first principles.

The limitations of classical diffusion theory for modeling light propagation in sea ice were investigated, and diffusion theory was used as a basis for inverting light field measurements to obtain scattering functions, which are very difficult to measure directly because of multiple scattering effects in even small ice samples.

Research in the microwave portion of the spectrum has resulted in new developments in the mathematical theory of inverse scattering particularly for one dimensional layered media, as well as the mathematical theory of homogenization, which relates the microstructural features of sea ice to its effective electromagnetic behavior. Significant refinements in approximate calculations of electromagnetic scattering from sea ice have also resulted. In conjunction, these advances have led to stable algorithms for recovering permittivity profiles, brine volume and other microstructural information [22].

Microwave experiment and theory focused on limiting assumptions of radiative transfer theory versus dense medium models of radiative transfer. Observations showed that the density of scatterers in sea ice is more than one inclusion per cubic millimeter for brine pockets. The bubble density in the near surface layers of multiyear ice is frequently this high also. The volume density of brine inclusions and bubbles is shown to be as much as tens per cubic millimeter. Each brine pocket presents a huge dielectric contrast with respect to ice, but fortunately the inclusions are small in the near surface layers of the ice examined. Consequently, the brine inclusions cannot in general scatter microwaves independent of one another and a dense media approach is required. If classical radiative transfer is used, there must be some ad hoc compensating factor to produce volume scattering at the proper level.

Several combined theoretical and experimetal studies attempted to identify microwave scattering contributions from the surface and from the volume. Scattering from very smooth (rms surface roughness less than 0.05 cm) ice was considered in several investigations [22,23]. For frequencies above 13 GHZ, analyses suggested that surface scattering dominated for incidence angles greater than 50 degrees. At higher frequencies (24) (17 GHz) the surface scattering dominates for angles less than about 25 degrees. However it is difficult to draw general conclusions about sea ice electromagnetics from these case studies . Measurement accuracies are difficult to assess because the ice was very smooth and backscatter is very sensitive to roughness slope and brine pocket size. .

An alternative approach investigated as part of the ARI is to use a process-oriented method with time-series data (sea ice growth, diurnal effects) to analyze the scattering mechanisms. In a given process, sea ice parameters are interrelated and governed by ice physics, which will determine the trend of the backscatter (not just the absolute backscatter level) in time-series measurements. Constrained by the physical trends, the scattering mechanisms can be identified depending on the resulting changes in roughness or volume parameters that cause the corresponding backscatter to increase or to decrease.

The process-oriented modeling is illustrated in Fig. 7 for C-band backscatter signature of a sea ice growth process undergoing diurnal thermal cycling [28]. The growth started in the early afternoon when the insolation was high causing a high ice surface temperature (lower panel in Fig. 7a). The ice sheet cooled down into the evening and the following night. The thermal variations were repeated over two cycles during which the ice sheet grew by 10 cm. Under the temperature cycling, brine volume changed (see upper panel in Fig. 7a) according to the eutectic phase distribution [29] forcing brine pocket size to increase and decrease by wall melting and freezing. Furthermore, values of complex permittivities of the constituents (ice and brine) in the inhomogeneous sea ice medium varied cyclically with the temperature variations. These interrelated processes caused the backscatter signature to cycle as observed in the experiment [28]. The model has to explain the observed backscatter cycles (both increasing and decreasing trends) with environmental and sea ice parameters constrained under these physical processes.

Figure 7b presents the model results at 25, 35, and 45 deg. incidence angles (see [28] for parameters used). At 25 deg, the weak backscatter cycles suggest an important contribution from rough surface scattering, which is not very sensitive to the thermal changes. At 35 deg, the stronger baskscatter cycles indicate a stronger contribution from volume scattering, which is very sensitive to the thermal variations due to the changes in brine volume and pocket size. At 45 deg, the baskscatter cycles are strong and the volume scattering mechanism is important. Furthermore, the model results capture the underlying decreasing trend due to the desalination process taking place during the ice growth (compare top of Fig. 7a with Fig. 7b). In view of inverse scattering models, the retrieval of sea ice geophysical parameters such as thickness is more successful when the remote sensing observations are sensitive to the ice growth process [26]. By relating remote sensing observables to physical processes, the models are useful to evaluate the conditions under which the geophysical parameter of interest can be obtained.

6.0 Conclusions and Implications

The ARI demonstrated how a broad-spectral, interdisciplinary approach could be applied to studying the relationships between sea ice physical and electromagnetic properties. As a consequence, the ARI improved our ability to interpret remote sensing data in terms of different sea ice types and for estimating ice thickness [22,25,26] as well as other geophysical parameters [27].

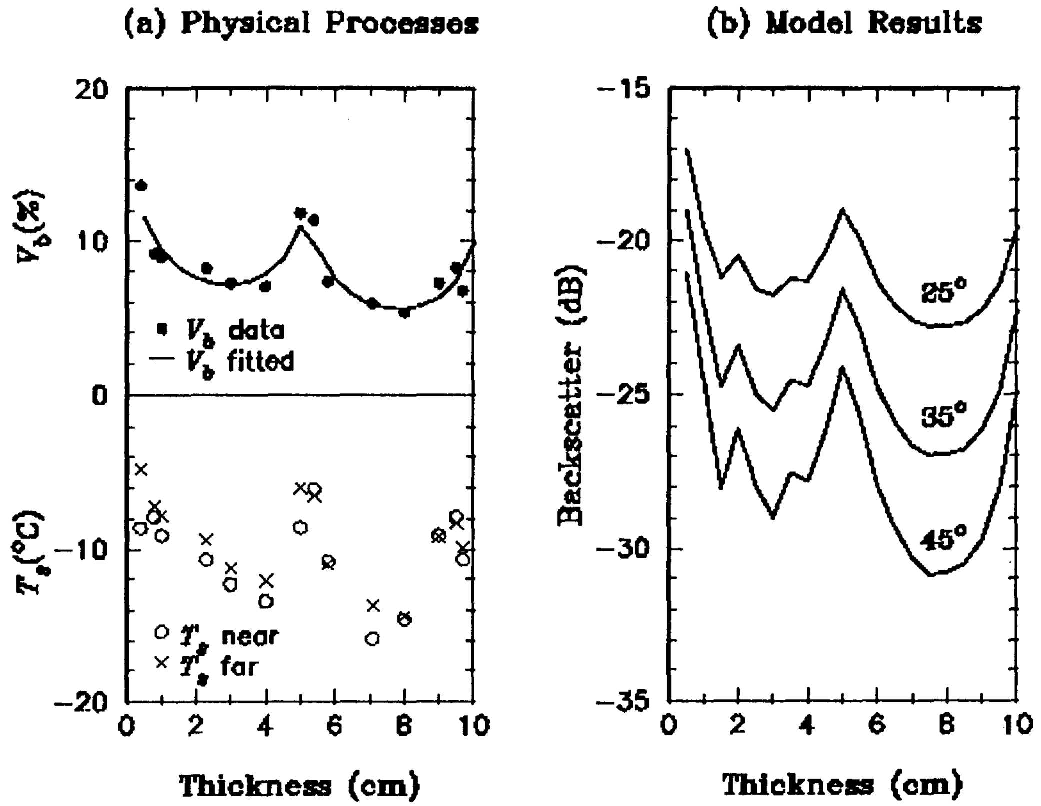

Figure 7: (a) Sea ice surface temperature Ts measured near the area of the radar foot prints and at the far side of the sea ice sheet, and the brine volume Vb corresponding to the temperature cycles, (b) Backscatter calculated at horizontal polarization and 25, 35, and 45 deg incidence angles for the ice growth process under diurnal thermal cycling.

There is a more general implication owing to the struggle to marry the efforts of a diverse group of investigators. By expanding discipline specific research objectives, overcoming limitations in terminology, understanding a wider range of measurement and analysis techniques, and establishing overarching physical objectives, it was possible to construct a rich experimental and theoretical program. The results of the program contribute to the groundwork for interpreting data from next generation sensors capable of observing earth's ice cover in exceptional spectral, temporal, and spatial detail.

7.0 Acknowledgements

Coordination of the Sea Ice Electromagnetics Accelerated Research Initiative was conducted under a grant from the Office of Naval Research. The research by the Jet Propulsion Laboratory was support by the Office of Naval Research through an agreement with the National Aeronautics and Space Administration.

8.0 References

[1] F.D. Carsey, Ed., Microwave Remote Sensing of Sea Ice. Washington DC: American Geophysical Union, Monograph 68, 1992

[2] Grenfell, T.C., D.G. Barber, A.K. Fung, K.C. Jezek, S.V. Nghiem, R.G. Onstott, D.K. Perovich, C.T. Swift and F. Tanis. Evolution of electromagnetic-signatures of sea ice from initial formation through the establishment of thick first-year ice. TGARRS same issue.

[3] Onstott, R.G., S.P. Gogineni, T.C. Grenfell, K.C. Jezek, D.K. Perovich, C.T. Swift. Electromagnetic and physical properties of sea ice formed in the presence of wave action. TGARRS same issue.

[4] Barber, D.G., A.K. Fung, T.C. Grenfell, S.V. Nghiem, R.G. Onstott, V. Lytle, D. K. Perovich, and A.J. Gow. The role of snow on microwave emission and scattering over first-year ice. TGARRS same issue.

[5] Gogineni, S., K.C. Jezek, L. Peters, J.D. Young, S.G. Beaven, and E.M. Nassar. Application of plane waves for accurate measurement of microwave scattering from geophysical surfaces. IEEE TGARS, vol 33, no 3, p. 627-633.

[6] Perovich, D.K., D. Barber, G. Cota, A.J. Gow, T.C. Grenfell, A.J. Hunt, R.A. Maffione, C.D.Mobley, R.O. Onstott, W.S. Pegau, and C.S. Roesler, Field observations of the electromagnetic properties of first-year sea ice, *TGARRS same issue.*

[7] Hunt, A.J., D.Miller, M.S. Quinby-Hunt, "Polarization-dependent measurements of sea ice," *Ocean Optics XII SPIE 2258,* J.S. Jaffe, Ed., 613-622, 1995.

[8] Maffione, R.A. and C.D.Mobley, Theory and measurements of the complete beam spread function of sea ice, Limnol. Oceanogr., in press.

[9] Perovich, D.K., C.S. Roesler, and W.S. Pegau, Variability in sea ice optical properties, *Journal of Geophysical Research,* accepted for publication.

[10] Roesler, C.S. and R. Iturriaga, Absorption properties of marine-derived material in Arctic sea ice, Ocean Optics 12, *Proc. SPIE Int. Soc. Opt. Eng.,* 2258, 933-943, 1994.

[11] Lytle, V.I, K.C. Jezek, S. Gogineni and A Hosseinmostafa, 1996. Field observations of microwave backscatter from Weddell Sea Ice. Int J. Rem Sensing, vol. 17 no 1 p 167-180.

[12] Lytle, V.I., K.C. Jezek, A.R. Hosseinmostafa and S. P. Gogineni, 1993. Laboratory Backscatter measurements over Urea ice with a snow cover at Ku band. IEEE TGARS, vol 31, no 5. p. 1009-1016.

[13] Hosseinmostafa, A.R., V.I. Lytle, K.C. Jezek, S. P. Gogineni, S.F. Ackley, and R.K. Moore, 1995. Comparison of radar backscatter from antarctic and arctic sea ice. Jour. Electromagnetic Waves and Applications, vol. 9, no. 3, p. 421-438.

[14] Kwok, R., S.V. Nghiem, S. Martin, D.P. Winebrenner, A.J. Gow, D.K. Perovich, C.T. Swift, D.G. Barber, K.M. Golden, and E. Knapp. Laboratory measurements of sea ice: connections to microwave remote sensing. TGARRS same issue.

[15] LeDrew. E.F. and D.G. Barber 1994. The SIMMS Program: A Study of Change and Variability within the Marine Cryosphere. *Arctic.* 47(3):256-264.

[16] Barber, D.G., and A. Thomas. 1998. The Influence of Cloud on the Radiation Balance, Physical Properties and Microwave Scattering of First Year and Multi-Year Sea Ice *IEEE Transactions on Geoscience and Remote Sensing*. 36(1): 38-50.

[17] Nghiem, S. V., R. Kwok, J. A. Kong, R. T. Shin, S. A. Arcone, and A. J. Gow, An electrothermodynamic model with distributed properties for effective permittivities of sea ice, Radio Sci., 31(2), 297-311, 1996.

[18] Barber, D.G., and S.V. Nghiem. 1997. On the Estimation of Snow Thickness Distributions over Sea Ice using Active Microwave Scattering. *Journal of Geophysical Research (Oceans).* In Review (Dec'97).

[19] Mobley, C.D., G.F. Cota, T.G.Grenfell, R.A. Maffione, W.S. Pegau, D.K. Perovich. Modeling light propagation in sea ice. TGARS same issue.

[20] Golden, K.M., M. Cheney, K.H. Ding, A.K. Fung, T.C. Grenfell, D. Isaacson, J.A. Kong, S.V. Nghiem, J. Sylvester, and D.P. Winebrenner. Forward electromagnetic scattering models for sea ice. TGARS same issue.

[21] Golden, K.M., D. Borup, M. Cheney, E. Cherkaeva, M.S. Dawson, K.H. Ding, A.K Fung, D. Isaacson, S.A. Johnson, A.K. Jordan, J.A. Kong, R. Kwok, S.V. Nghiem, R.G. Onstott, J. Sylvester, D.P. Winebrenner, and I.H.H. Zabel. Inverse Electromagnetic Scattering Models for Sea Ice. TGARRS same issue.

[22] Zabel, I.H.H., K.C. Jezek, S.P. Gogineni, and P. Kanagaratnam. Search for proxy indicators of young sea ice thickness. Jour. Geophys. Res., vol. 101, no. C3, p. 6697-6709, 1996.

[23] Beaven, S.G., G.L. Lockhart, S.P. Gogineni, K. Jezek, A.R. Hosseinmostafa, A.J. Gow, D.K. Perovich, A.K. Fung and S. Tjuata. Laboratory Measurements of Radar Backscatter from Bare and Snow-Covered Saline Ice Sheets. International Journal of Remote Sensing, vol. 16, no. 5, p. 851-876, 1995.

[24] Bredow, J. A. Fung, R. Porco, R. Hosseinmostafa, K.C. Jezek, L. Peters, J. Young and A. Gow. An experimental study of relative contributions from surface and volume scattering mechanisms in saline ice. in Proceedings IGARSS =9194, Pasadena, CA., vol 1, p. 608-610, 1994.

[25] Cheney, M., D. Isaacson, V.I. Lytle, and S.F. Ackley. Recovery of surface parameters from stepped-frequency radar returns. TGARRS same issue.

[26] Shih, Shih-En, Kung-Hau Ding, Son V. Nghiem, Chih-Chien Hsu, Jin Au Kong, and Arthur Jordan. Thin saline ice thickness retrieval using time series C-band polarmetric radar measurements. TGARS same issue.

[27] Adams, R.J., and G.S. Brown. A model for altimeter returns from penetrable geophysical media. TGARRS same issue.

[28] S. V. Nghiem, R. Kwok, S. H. Yueh, D. K. Perovich, A. J. Gow, C. C. Hsu, K. H. Ding, J. A. Kong, and T. C. Grenfell, ``Diurnal thermal cycling effects on backscatter of thin sea ice," IEEE Trans. Geosci. Remote Sens., vol. 36, no. 1, pp. 111-124, 1998.

[29] G. F. N. Cox and W. F. Weeks, ``Equations for determining the gas and brine volumes in sea-ice samples," J. Glac., vol. 29 no. 12, pp. 306-316, 1983.